Performance comparison between TEMO and a typical FMS in presence of CTA and wind uncertainties

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***Abstract*—Continuous Descent Operations (CDO) with Controlled Times of Arrival (CTA) at one or several metering fixes could enable environmentally friendly procedures without compromising airspace capacity. Extending the current capabilities of state-of-the-art Flight Management Systems (FMS), the Time and Energy Managed Operations (TEMO) concept is able to generate optimal descent trajectories with an improved planning and guidance strategy to meet CTA. The primary aim of this paper is to compare the performances of TEMO (in terms of fuel consumption and time error) with respect to a typical FMS, that is an FMS without re-planning mechanism during descent based on time or altitude errors. The comparison is performed through simulation, using an A320-alike simulation model and considering several scenarios in presence of CTA and wind uncertainties. Results show that TEMO is capable of guiding the aircraft along a minimum fuel trajectory still complying with a CTA, even if significant wind prediction errors are present. For a same scenario, a typical FMS without re-planning capabilities or tactical time-error nulling mechanism during the descent, would miss the CTA in most cases.**

I. Introduction

The reduction of the environmental impact of aviation is one of the major drivers of current research efforts in air transportation. Continuous Descent Operations (CDO) aim at executing fully engine-idle descents to reduce both fuel consumption and noise nuisance[1]. Unfortunately, the operational use of CDO in busy airports reduces runway capacity as Air Traffic Controllers (ATC) are forced to introduce spacing buffers to ensure safe separation between aircraft.

The introduction of trajectory-based operations in the near future will help to mitigate these problems by allowing the ATC to safely handle more traffic. Initial 4D (i4D) operations is a first step to evolve towards a concept of trajectory-based operations. During the introduction of i4D operations, Controlled Time of Arrival (CTA) will be given to each aircraft converging to a metering fix (e.g. the Initial Approach Fix, IAF) in order to sequence the arriving traffic in a congested airport.

To achieve fuel and noise reductions whilst fulfilling the incoming CTA, new avionic systems and operational concepts need to be developed. Extending the capabilities of state-of-the-art Flight Management Systems (FMS), the Time and Energy Managed Operations (TEMO) concept is able to generate optimal descent trajectories with an improved planning and guidance strategy to meet CTA time constraints[2], [3], [4].

The TEMO concept involves both trajectory prediction and guidance functions. While the aircraft is still in cruise, the TEMO trajectory predictor computes an optimal flight profile according to a predefined criteria (e.g. minimum fuel, minimum time, etc.). The optimisation of the descent trajectory is formulated as an optimal control problem and solved by means of direct collocation methods[5].

Once the descent has been initiated, TEMO uses strategic re-planning guidance to achieve the environmental goals whilst fulfilling the CTA: associated with a flight profile, maximum allowable energy and time errors are defined. During the descent execution, the time and energy errors with respect to the active flight profile are continuously monitored. If the maximum allowable energy and/or time error boundaries are exceeded due to model inaccuracies and other sources of uncertainty, the active flight profile is updated with a (new) optimised flight profile computed in real-time. A new (or updated) CTA will also trigger a re-plan.

Different from the TEMO strategic re-planning concept, typical FMS guidance strategies do not compute a new plan once the descent has been initiated even if the deviations from the scheduled time, path and/or speed are significant. Instead, different tactical guidance modes will engage to steer the aircraft in the computed flight profile. However, in most typical FMSs these guidance modes do not allow for a tactical time-error nulling mechanism.

In previous research[6], TEMO was already compared with a typical FMS showing improvements regarding time adherence performance and environmental impact. Nevertheless, these results could not be generalised because only a particular scenario was analysed. The primary aim of this paper is to extend this comparison to several scenarios in presence of CTA and wind uncertainties.

Following the same methodology, two A320-alike simulation models equipped, respectively, with TEMO and a typical

FMS have been implemented in Simulink and several descents have been simulated assuming a requested CTA at the Final Approach Point (FAP). Total fuel burn and time errors with respect to the CTA for different scenarios with wind prediction errors have been chosen as performance indicators for the comparison.

II. Background

The goal of this section is to serve as introduction to the basic functionalities of an FMS and the TEMO concept. Section II-A addresses the fundamentals of a typical FMS. In Section II-B the TEMO concept is presented.

A. FMS fundamentals

In this paper, the generic FMS is broken into two major components: the trajectory predictor and the control and guidance. Fig. 1 shows the interaction between them.

Well before the Top Of Descent (TOD), during the cruise phase, the trajectory predictor constructs the optimal four-dimensional flight profile that the aircraft is intended to fly. This flight profile is based upon the flight plan, the weather forecast and aircraft performance data.

On the one hand, the lateral flight plan consists of a variety of procedure legs and waypoints (i.e. the route). On the other hand, the vertical flight plan is composed by a set of speed, altitude and/or time constraints at one or several waypoints along the route, the cruise altitude and the cost index (CI)[1].

Regardless of the FMS type, the algorithms used by the trajectory predictor require a model for the aircraft dynamics. Most FMSs are expected to adopt a non-linear point-mass representation of the aircraft in which the sate vector $\boldsymbol{x} = [v\ s\ h\ m]^T$ is composed, respectively, by the true airspeed (TAS), the along path distance, the altitude and the mass. The dynamics of this state vector are particularised by the following system of Ordinary Differential Equations (ODE):

$$\begin{aligned} \frac{\mathrm{d}v}{\mathrm{d}t} &= \dot{v} = \frac{T-D}{m} - g\sin\gamma \\ \frac{\mathrm{d}s}{\mathrm{d}t} &= \dot{s} = v\cos\gamma \\ \frac{\mathrm{d}h}{\mathrm{d}t} &= \dot{h} = v\sin\gamma \\ \frac{\mathrm{d}m}{\mathrm{d}t} &= \dot{m} = -FF, \end{aligned} \tag{1}$$

where T is the aircraft thrust; D is the aerodynamic drag; g is the gravity acceleration; γ is the aerodynamic flight path angle and FF is the fuel flow.

Typical FMSs compute the flight profile by numerical integration of Eqns. (1). Several forms of these equations are used to accommodate constant Calibrated Airspeed (CAS) or Mach, fixed flight path angle, vertical speed, deceleration, and level flight phases. This numerical integration usually starts at the destination runway threshold (RWY) and is computed backwards up to the current aircraft position. Termination of a phase can occur when a new maneuver type must be used due to encountering an altitude or speed constraint.

It is important to have in mind that modern FMSs could use other advanced techniques (such as optimal control) to generate the optimal flight profile.

Once computed, the flight profile is provided to the control and guidance component, which computes commands for the elevator, aileron, and throttle to steer the aircraft to capture and maintain the planned route, vertical path, speed and/or time given the current states estimated by the aircraft sensors. These commands may change form depending on the particular flight controls equipment and guidance logics installed on a given aircraft.

B. The TEMO concept

The TEMO concept involves both trajectory prediction and guidance functions and is based on some basic energy principles. The total energy E_t of an aircraft is the sum of its kinetic energy E_k and potential energy E_p:

$$E_t = E_k + E_p = \frac{1}{2}mv^2 + mgh. \tag{2}$$

The energy rate can be obtained by differentiating Eqn. (2):

$$\dot{E}_t = mv\dot{v} + mg\dot{h}. \tag{3}$$

By combining Eqns. (3) and (1) the total energy rate can be expressed in terms of the forces acting upon the aircraft:

$$\dot{E}_t = v\left(T - D\right). \tag{4}$$

According to Eqn. (4) the total energy of an aircraft can be increased by applying thrust and decreased by increasing drag. In addition, the law of conservation of energy states that potential energy can be exchanged for kinetic energy and vice versa through energy modulation. It is well known that thrust and speed-brakes are the most effective means of increase and decrease the total energy of the aircraft, whereas elevator control provides an effective mean to modulate energy.

During a TEMO descent the aircraft engines are set to idle thrust and the use of speed-brakes is minimised, in order to reduce the fuel consumption and noise nuisance. In such conditions, it is still possible to trade altitude for acceleration and vice versa using elevator control only, adjusting the airspeed by means of energy modulation. Namely, if the aircraft requires a higher velocity, it could loose altitude instead of applying additional thrust. Alternatively, it could reduce speed by pitching up instead of using drag devices.

Well before TOD, the TEMO trajectory predictor calculates an optimised descent trajectory, which minimises the use of speed-brakes and thrust (or fuel) whilst adhering to operational, aircraft and ATC constraints. Different from a typical FMS, the optimisation of the trajectory is formulated as an optimal control problem and solved by means of direct collocation methods[6], [5]. This approach guarantees the optimallity of the resulting trajectory, which cannot be ensured

[1] The cost index is a number representing the ratio of the time-related cost of an aircraft operation and the cost of fuel

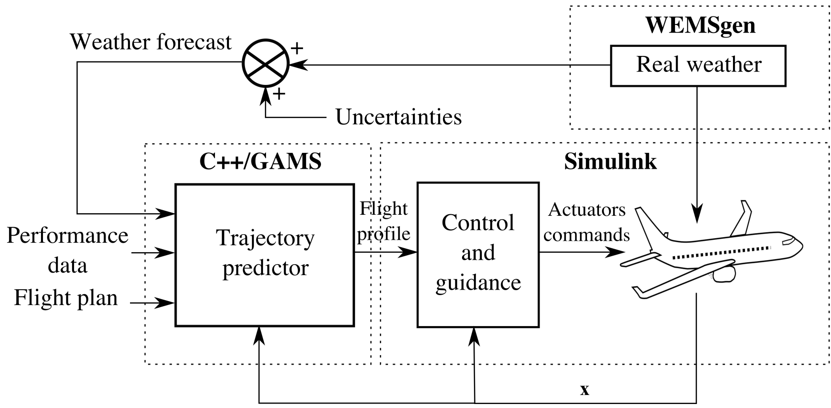


Fig. 1. Simulation framework architecture

by using simple numerical integration of Eqn. (1) with pre-calculated optimal speeds obtained from look-up tables.

Fast Optimisation for Continuous Descent Approaches (FASTOP), developed under the CleanSky programme, is an existing implementation of such a trajectory optimiser suitable for use in TEMO[7]. The flight profile computed by FASTOP is a speed plan, and is executed by means of speed on elevator control. Consequently, the altitude may deviate from the planned path to maintain the planned speed due to unforeseen disturbances (such as unexpected winds or inaccuracies in the model).

In a strategic guidance concept, the time and energy errors with respect to the plan are continuously monitored during the descent execution. If the maximum allowable energy and/or time error boundaries are exceeded the current flight profile is updated with a (new) optimised flight profile, given the current state, applicable constraints and optimality objectives.

FASTOP aims to improve the performance of the TEMO optimisation engine in terms of execution time and accuracy of the model, in order to minimise the number of re-plans when using such strategic guidance concept.

Figure. 2 shows an schematic overview of the strategic re-planning guidance concept. For further technical details, the reader is referred to the excellent work of Ref. [4].

III. Typical FMS and TEMO models

In this Section the typical FMS and TEMO algorithms implemented for the comparison are presented. Section III-A presents the models adopted for the trajectory predictor and control and guidance functions of the typical FMS considered in this paper. Analogously, Section III-B presents the TEMO trajectory prediction and guidance algorithms.

A. Typical FMS model

The FMS algorithms are proprietary to the FMS manufacturer, and so detailed algorithmic documentation is not available. Consequently, some assumptions have been taken into account when modelling the typical FMS, trying always to mimic with the maximum fidelity its real behavior.

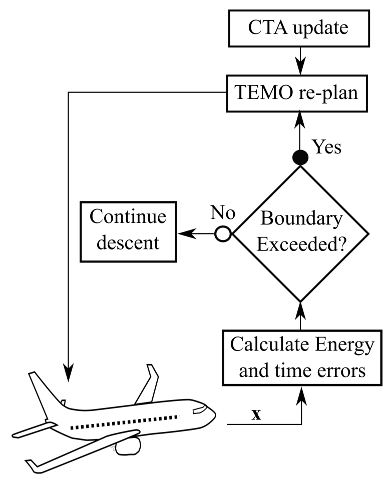


Fig. 2. Strategic re-planning guidance concept

1) Trajectory predictor: The typical FMS flight profile is divided in several phases and is computed by backwards integration of Eqns. (1), starting at the destination runway threshold up to the current aircraft position.

When building the descent flight profile, the goal is to minimise the number of geometric segments[2](and fuel consumption). If an idle segment or a single geometric segment can fulfill all the constraints of the vertical flight plan, it is used. Obviously, preference is given to idle segments.

Internally, the FMS divides the descent path into several phases, depending on the relative position of the applicable constraints[8]. The resulting flight profile starts at the TOD by setting up an idle segment that takes the aircraft to the first altitude constraint that cannot be flown at idle thrust T_{idle}, and follows this with geometric segments between constraints. Namely, the typical FMS will calculate the flight profile taking all the constraints from the vertical flight plan into

[2]The trajectory predictor computes these segments assuming that the autopilot will control the target path, and the autothrottle will control the target speed (not necessarily at idle thrust). In such segments, the needed thrust must be computed accordingly.

consideration by altering the angle of the geometric segment (or segments if more than one constraint is present), then adding the idle segment to finally work out the TOD position.

It should be noted that the idle segments are computed by assuming $T_{idle} + \Delta$, where Δ is known as the idle factor. This additional (small) amount of thrust helps to face model inaccuracies and other sources of uncertainty, allowing the autothrottle to command further thrust reduction as the last mean of loosing energy to stay on the scheduled path.

For each phase, the FMS trajectory predictor uses the optimal CAS or Mach speeds obtained from pre-calculated look-up tables bundled into the FMS database. These optimal speeds (also known as economic speeds) are functions of the CI, the weather forecast, the cruise level and the landing mass.

The weather forecast consists on a wind prediction generated by linear interpolation with wind data (wind magnitude and true direction) at five different altitudes and for several waypoints; together with the International Standard Atmosphere (ISA) temperature and pressure profiles corrected for the temperature deviation with respect to the ISA and the barometric pressure adjusted to sea level (QNH), respectively.

As a result of the backwards integration, a "near-optimal" flight profile is obtained, which may include levelled and/or geometric segments that are not flown at idle thrust.

In case that a CTA were requested by the ATC prior the descent, the typical FMS would iterate with the CI until the computed trajectory satisfies the time constraint.

2) Control and guidance: During the execution of the descent, different guidance modes engage depending on the situation. The typical FMS considered in this paper will not compute a new flight profile after the TOD even if the deviations from the scheduled flight profile are significant.

Instead, the typical FMS steers the aircraft along the descent flight profile by controlling targets for the elevator and throttle, which are managed by the autopilot and autothrottle, respectively. Both autopilot and autothrottle own different guidance modes which activation are triggered by certain events.

The so-called *speed* and *thrust* guidance modes have been considered for the autothrust model. For the former, the autothrottle controls the throttle to maintain the target speed (either CAS or Mach). For the latter, the autothrottle controls the throttle to maintain the desired amount of thrust.

Regarding the autopilot, both *speed* and *path* modes have been implemented. In path mode the aircraft is guided towards the selected altitude throughout the scheduled path by means of elevator commands, taking into account possible altitude constraints. In such situation, the autothrottle may be either in thrust or speed mode. Conversely, when flying with the autopilot in speed mode the elevator is controlled to maintain the target speed and the autothrottle stays in thrust mode.

The autopilot path mode is activated at the TOD. While the aircraft is on path[3], the autothrottle keeps the thrust at $T_{idle}+\Delta$, where Δ (if in a idle segment) or the required thrust to maintain the planned speed (if in a geometric segment).

[3]The aircraft is considered on path when the vertical deviation from the planned path is less than 50 ft

When flying an idle segment on path, a speed range defines acceptable speed variations around the scheduled speed to account for uncertainties (± 20 kt in absence of speed constraints or $+5/20$ kt otherwise). The autopilot is allowed to modify the speed within this range in order to follow the planned path.

If the speed reaches the upper bound, the vertical autopilot reverts from path to speed mode maintaining that speed and the autothrottle reduces the thrust to idle aiming to intercept the path from above. If these actions do not increase the descent angle enough, the aircraft deviates from the descent profile and the pilot must deploy half speed-brakes (or full speed-brakes if needed). On the contrary, if the lower bound of the speed range is reached the autothrottle reverts to speed mode while the autopilot follows the planned path.

Table I summarises the different combinations of autopilot-autothrottle modes depending on the aircraft situation.

TABLE I
FMS GUIDANCE MODES

Situation	Autopilot	Autothrottle
Cruise	Path (altitude)	Speed
Descent on path (idle segment)	Path	Thrust ($T_{idle} + \Delta$)
Upper speed limit reached	Speed	Thrust (T_{idle})
Lower speed limit reached	Path	Speed
Geometric segment	Path	Speed

It should be noted that best-in-class FMSs update the Estimated Time of Arrival (ETA) predictions also during descent and when a time error bound (which depends on distance to the CTA point) is exceeded the entire profile is recomputed with new speeds (i.e. iterating with cost index) in order to correct the time error. One of the main differences with TEMO is that the new plan (of the best-in-class FMS) does not consider the current 3D position of the aircraft. As a consequence the aircraft will always end up either above or below the new vertical path and the aircraft will use tactical guidance to return to the vertical path.

B. TEMO

1) Trajectory predictor: In contrast to the typical FMS, TEMO trajectory predictor computes the flight profile by formulating and solving a multi-phase optimal control problem by means of direct collocations methods[5], [9]. The TEMO descent is split into different phases, where different operational constraints apply. More details about the TEMO phases and their associated constraints can be found in Ref. [7].

The Non Linear Programming (NLP) solver used to solve the optimal control problem is executed from a starting point with all the variables of the problem initialised at the values obtained from a guess. For the guess generation an initial value problem is set for each phase within the flight profile. A specific event triggers the transition from one phase to the following one, starting at the runway THR and integrating Eqns. (1) backwards until reaching the current aircraft position. Different from the typical FMS, TEMO trajectory predictor uses idle thrust without considering Δ.

For the optimization process some flexibility is added, allowing the aircraft to descent within some deceleration margins. These upper and lower bounds form the principal path constraints of the optimisation problem.

The TEMO optimisation process takes into account only a subset of the flight phases of this guess. In particular, the phases from the actual aircraft position when requesting the re-plan down to the Instrumental Landing System (ILS) glide slope (G/S) interception. From this point on, the guess is taken. The reason behind this is to simplify the optimisation engine, keeping in mind that when descending on the ILS G/S, there is no room for energy modulation. The state variables at the final point of the optimised trajectory (if going forward in time) are linked to the last point of the guess (if going backwards in time) that is not considered during the optimisation process.

2) Control and guidance: In the current implementation, TEMO uses strategic re-planning for both time and energy to meet the environmental and spacing goals. Associated with the active flight profile along the descent, maximal allowable energy and time (if a CTA is present) deviations are defined.

At cruise, the aircraft flies with the autopilot and autothrottle in altitude and speed modes, generating elevator and throttle commands to keep the cruise altitude and Mach, respectively.

During the descent, from the active flight profile the CAS at a given distance from runway THR is derived and fed to the autopilot, which controls the elevator to follow the CAS plan. Once the system detects time and/or energy deviations greater than the defined time and energy error boundaries, TEMO trajectory predictor generates a new profile starting at the current aircraft position to correct the deviations.

If the deviation is too large to satisfy all constraints, the algorithm calculates an energy-optimal trajectory that uses minimised amounts of thrust and speed-brakes. However, situations could occur that an energy-optimal solution cannot be achieved as well, resulting in a re-plan being rejected. This can be due to the definition of a TEMO descent or too limiting constraints. In these cases, pilots would notify ATC that an optimised descent is not feasible whilst satisfying all active constraints and negotiate new constraints.

IV. Architecture

The simulation environment is broken into several components, which interactions are depicted in Fig. 1. The trajectory predictor and the control and guidance modules are part of the FMS functionalities, one component mimics the real weather and the last component models the aircraft dynamics.

The trajectory predictor receives the flight plan along with the weather forecast and aircraft performance data to compute the flight profile, based on this data and the current aircraft position. FASTOP, which core is written in C++, is used as a trajectory predictor for both typical FMS and TEMO.

Once the required data are provided to FASTOP, a numerical backwards integration of Eqns. (1) is performed starting at the runway THR up to the current aircraft position using the specific algorithms of the concerned FMS (see Section III for more details). As a result of the numerical backwards integration, a feasible and sub-optimal trajectory is obtained.

This trajectory is directly fed to Simulink as the descent flight profile provided that a typical FMS descent is simulated. If a TEMO descent is simulated, the states and control of this trajectory become the guess for the NLP process. The guess is provided to GAMS, which solves the problem using CONOPT.

The weather is initialised with recorded weather data in GRIded Binary (GRIB) formatted files. However, for optimisation solvers to work efficiently, continuity and differentiability for the right hand sides of the model equations are required. Typically, weather data cannot be accurately approximated by means of polynomial functions. In addition, this approach is prone to oscillation due to the Runge's phenomenon, leading to poor convergence and/or local minima issues.

In order to face this problem, WEMSgen[10] has been integrated into the simulation environment to provide weather data for both trajectory prediction and simulation purposes. WEMSgen achieves C^2 continuity by approximating the weather data by tensor product cubic B-splines[11].

The weather forecast is an estimation of the actual weather and some errors might exist. The weather forecast is generated by adding an offset to the actual weather data to take into consideration possible uncertainties.

The flight profile is updated whenever a re-plan is requested by an excessive time or energy error. It should be noted that the typical FMS calculates and freezes the initial flight profile before the TOD. Accordingly, re-plan requests may be triggered only during TEMO simulations.

Finally, the flight profile is fed to the control and guidance function, which output are the actuators commands. Given these commnads, the actuators are the mechanism by which the control system acts upon the aircraft.

V. Test harness and results analysis

This section presents the results obtained during the performance comparison of TEMO and a typical FMS for several case studies. In SectionV-A the experimental setup is described. In Section V-B an example of scenario is discussed. Finally, Section V-C the overall results are summarised.

A. Experimental setup

The following scenario has been considered in this paper: an airbus A320 with a scheduled landing mass corresponding to 90% of the Maximum Landing Mass (MLM) is cruising at FL360 and M0.78, aiming to descent at Eelde airport (in the Netherlands) using the REKEN1G STAR followed by the TOLKO1G RNAV ILS CAT-I approach for runway 23. 150 NM before the runway THR, the ATC notify a CTA at the FAP, which implies to reach the concerned point in 24 minutes.

The effects of wind prediction errors on the performance differences between TEMO and the typical FMS have been analysed for several scenarios by adding different offsets to the real weather (see Fig. 1).

The overall set of scenarios is divided into two subsets depending on the model adopted for the real weather component: the simulations of the first subset have been carried out assuming the ISA atmosphere and calm winds; for the second subset, recorded weather data from the April 10th 2012 over The Netherlands have been taken.

Figure. 3 shows the temperature, pressure and winds at the region of interest for three different altitudes. The route along with the IAF (TOLKO) and FAP (EH512) corresponding to the selected procedure are also shown for illustrative purposes.

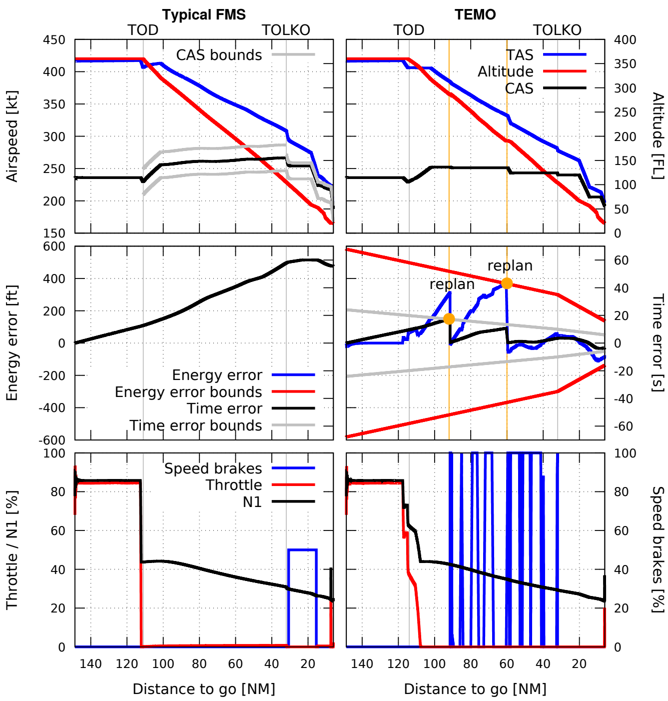


Fig. 4. Simulation in presence of a wind direction error of $-20°$

The scenario without wind prediction errors of the ISA subset using the typical FMS has been taken as a reference. Total fuel burned for the remaining simulations are shown as the relative fuel differences from such reference scenario.

For the TEMO scenarios it has been assumed that if an infeasible solution is obtained as a result of a re-plan optimisation the pilot would select either the earliest or the latest trajectory to the waypoint at which the CTA is requested.

B. Example of simulations

Fig. 4 shows the simulation for the scenario for the recorded weather data subset in presence of $-20°$ of wind direction error. Results are shown as a function of s down to the FAP.

The first and second columns show the results for the typical FMS and TEMO, respectively. The top row Figures show the speed and altitude executed during the descent. For the typical FMS, ± 20 kt of CAS deviation is allowed from the TOD to TOLKO. After TOLKO the upper bound reduces to $+5$ kt due to encountering a speed constraint.

Second row shows the time and/or energy errors along with the considered boundaries (if any). For the typical FMS simulation, the FAP is reached with more than 50 s time error.

For the TEMO simulation, the first re-plan is triggered by an excessive time error almost at 90 NM form the runway THR. When the first re-plan becomes active both energy and time errors are close to zero since the aircraft is following the newly computed path, speed and time. The second re-plan is triggered at 60 NM from the runway THR by an excessive energy error reaching the lower bound. Thanks to the strategic re-planning concept, TEMO reaches the FAP with less than 5 seconds error, thus complying with the requested CTA.

The last row shows the throttle and speed-brakes use throughout the descent. After TOLKO, the typical FMS needs to significantly reduce the CAS to keep it within the allowed bounds. Even if keeping the speed at the upper bound ant the thrust at idle, the wind prediction error is so high that half-speed brakes is needed to increase the descent angle aiming to intercept the path from above.

For neither of the TEMO re-plans energy modulation through the elevator sufficed. Both re-plans claimed the use of speed-brakes in order to comply with the constraints.

C. Results

In the following Sections the results obtained for the ISA and recorded weather scenarios with a CTA at the FAP are presented. Total fuel burned and time error at the FAP are throughly discussed as a function of the wind prediction errors.

1) ISA subset: Fig. 5(a) shows the typical FMS and TEMO relative fuel differences (with respect to the reference scenario) and the TEMO fuel savings as a function of the wind prediction errors for the ISA subset. In such scenarios, the weather forecast considers different combinations of wind speeds and directions while during the simulation no winds are used.

Fig. 6(a) shows the time error with respect to the CTA and the number of TEMO re-plans for these wind prediction errors.

According to Fig. 5(a), considering south and west winds into the weather forecast lead less fuel consumption (if compared with the reference scenario) and TEMO fuel savings $(1.5 - 2.6\%)$. Conversely, in presence of north and west wind fuel burned is higher (regardless of the FMS considered) and fuel savings decrease. Even in some cases the typical FMS achieves less fuel consumption if compared with TEMO. However, for those scenarios in which TEMO burns more fuel, the typical FMS reaches the FAP with more than 20 seconds error (e.g. 10 kt of north wind).

Remember that the typical FMS guidance component modelled in this paper does not generate a new descent profile regardless the time errors with respect to the CTA. In addition, no error nulling mechanism for time deviations has been considered. Adversely, TEMO continuously monitors time errors and triggers a re-plan whenever the time error reaches the allowable boundaries. These re-plans may eventually request the use of throttle to comply with the CTA, resulting in more fuel burned if compared with the typical FMS dormant behavior with respect to time errors.

For the scenarios with north and west wind prediction errors, the typical FMS reaches the FAP with an impermissible time error (higher than 20 s) while TEMO is able to comply with the CTA with less than 7 s error. As a final remark, no more than 3 re-plans have been triggered for all the simulations

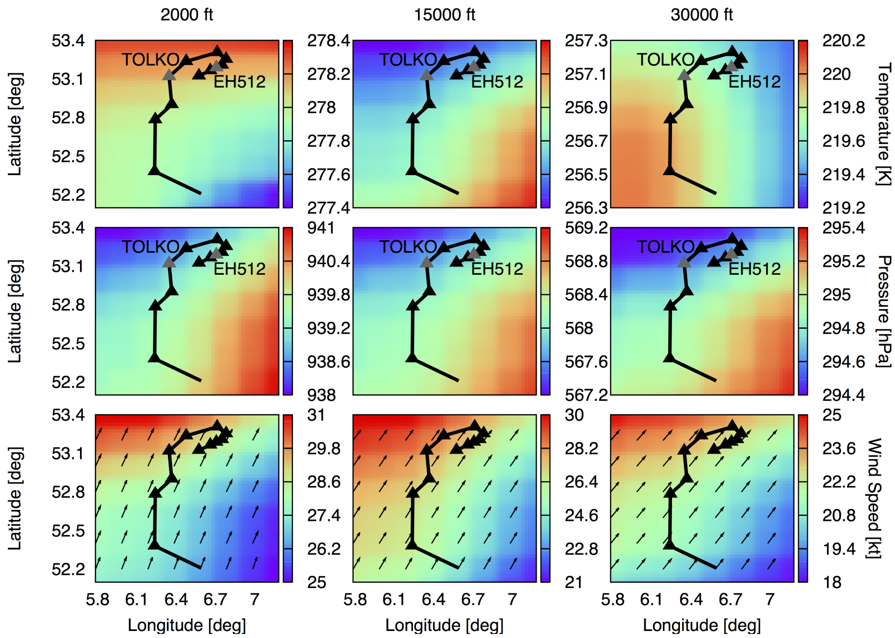
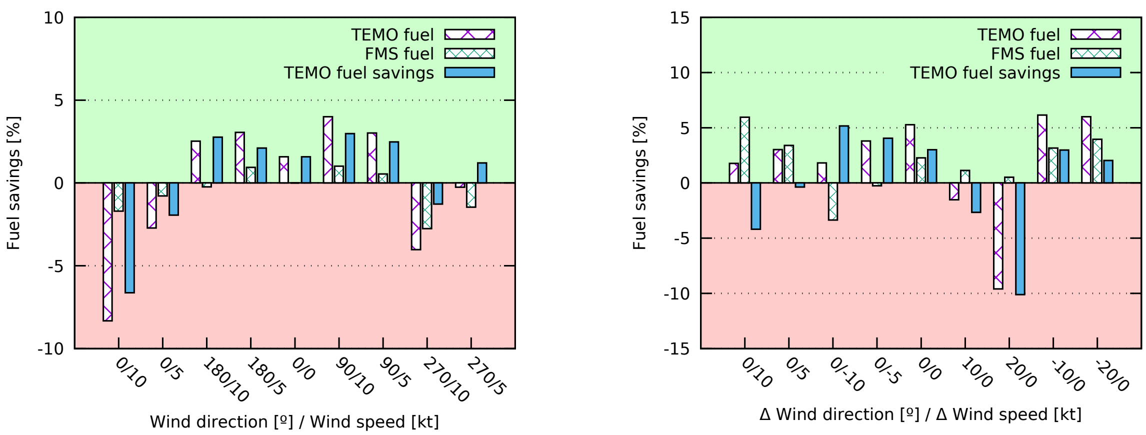


Fig. 3. Recorded weather data and route



(a) ISA

(b) Real weather

Fig. 5. Fuel consumption and TEMO fuel savings

shown hereby. This fact evidences the enhancements in the model that FASTOP has provided to the TEMO concept.

2) Recorded weather data subset: Fig. 5(b) shows the typical FMS and TEMO relative fuel differences and the TEMO fuel savings as a function of the wind prediction errors for recorded weather data subset. In such scenarios, wind prediction errors are modelled by adding wind speed and/or wind direction biases to the real weather.

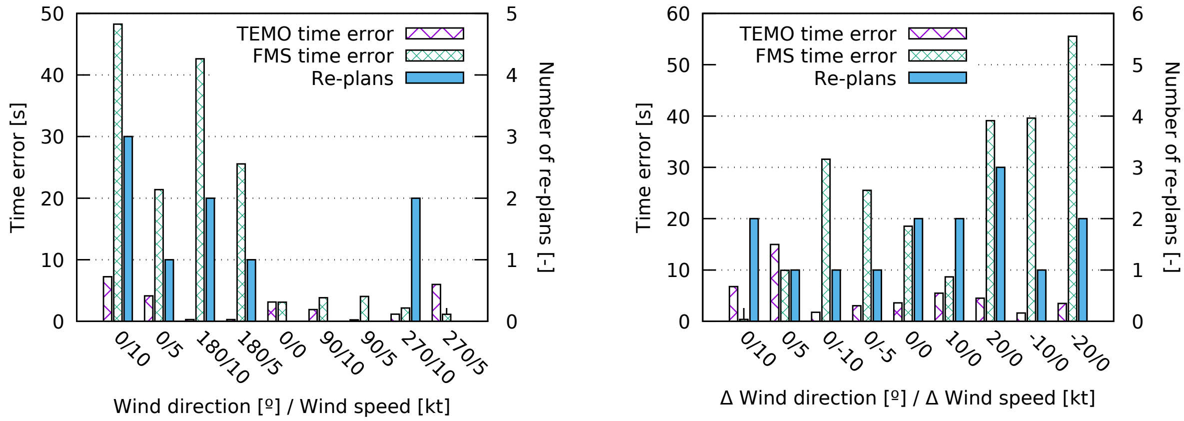
Fig. 6(b) shows the time error with respect to the CTA and the number of TEMO re-plans for these wind prediction errors.

Accordin to Fig. 5(b) for this particular route negative wind speed or wind direction biases lead, in general, to less fuel consumption than for the reference scenario and TEMO fuel savings up to 5%. For the complementary scenarios, the typical FMS achieves less fuel burned if compared with TEMO.

For all the scenarios presented in Fig. 6(b), TEMO achieves the FAP with less than 15 s error, being the simulation with a wind speed bias of 5 kt a descent in which a infeasible re-plan was obtained and the earliest flight profile was selected.

As for the ISA subset, the time errors with respect to the CTA for the typical FMS simulations are much higher (with a maximum of 55 s) than for the TEMO descents. Nevertheless, in some scenarios the wind prediction error has worked in favor of the time error for the typical FMS and the FAP has been achieved with almost no time error using neither strategic nor tactical time-error nulling mechanism.

In presence of wind speed errors, the curved shape of the procedure flown (with almost a 180° turn) leads to an increasing time error (in absolute terms) before EH741 and a decreasing time error afterwards, resulting in an almost



(a) ISA

(b) Real weather

Fig. 6. Time errors and number of TEMO re-plans

null global time error for certain scenarios. However, TEMO guidance is continuously monitoring the time and energy errors an solving them using strategic re-planning. Current TEMO algorithm does not look at the past weather forecast errors and is not able to predict that by flying the active flight profile without strategic intervention time and/or energy errors would decrease again.

VI. Conclusions

To achieve fuel and noise reductions and to meet assigned CTA, new avionic systems and concepts are needed. Different from most state-of-the-art Flight Management Systems (FMS), Time and Energy Managed Operations (TEMO) concept is able of generating optimal trajectories according to a predefined criteria (e.g. fuel or noise) with enhancements to the weather forecast model and with an improved ability to meet time constraints at one or more fix within the lateral route.

In this paper, the TEMO concept has been compared with a typical FMS behavior in presence of Controlled Time of Arrival (CTA) at the Final Approach Point (FAP) and wind uncertainties. Total fuel burned and time error with respect to the CTA have been chosen as performance indicators for the comparison. The results have been obtained for several case studies using an Airbus A320 alike simulation model. Several descents from the cruise phase to Eelde airport (in the Netherlands) have been simulated and the effects of certain wind prediction errors on the performance differences have ben analysed.

For all the scenarios considered herein, TEMO achieves the FAP with less than 15 seconds error. In general, for the typical FMS simulations the time errors with respect to the CTA are much higher (with a maximum of 55 seconds) than for the TEMO descents. In addition, for those scenarios in which both TEMO and the typical FMS have complied with the CTA, the former tends to achieve fuel savings up to 5%.

These results demonstrate that TEMO concept is capable of guiding the aircraft along an optimal trajectory in terms of fuel still complying with a CTA, even if significant wind prediction errors are present. For a same scenario, a typical FMS without neither re-planning capabilities nor tactical time-nulling mechanisms during the descent, would miss the CTA in most cases.

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